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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA 3, CALIFORNIA

407-2

National Aeronautics and Space Administration
Contract No. NASw-6

Technical Release No. 34-42

INSTRUMENTATION FOR RESEARCH ON COMBUSTION INSTABILITY IN SOLID-PROPELLANT ROCKET MOTORS

F. W. Spaid
E. M. Landsbaum

JET PROPULSION LABORATORY
A Research Facility of
National Aeronautics and Space Administration
Operated by
California Institute of Technology
Pasadena, California
April 1, 1960

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F. W. Spaid[2]
E. M. Landsbaum[3]

ABSTRACT

Research on combustion instability in solid-propellant rocket motors places unusually severe requirements on instrumentation systems. A high-frequency system that correctly obtains amplitude and frequency data is required. Determination of the phase relationship between oscillations in different parts of the chamber is also useful. The high-frequency gauges must be reliable and relatively insensitive both to high rates of heat transfer and to high accelerations. A low-frequency pressure gauge and system that correctly obtains the mean chamber pressure is also required. A discussion of the systems in use at the Jet Propulsion Laboratory is given. The systems are discussed from the viewpoint of the user: that is, the reliability of the information obtained.

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[1]Portions of this paper were originated under studies conducted for the Department of the Army, Ordnance Corps, under Contract No. DA-04-495-Ord 18. Such studies are now conducted for the National Aeronautics and Space Administration, under Contract No. NASw-6.

[2]Associate Research Engineer, Solid Propellant Rockets Section.

[3]Research Group Supervisor, Solid Propellant Rockets Section; member, ARS.

I. INTRODUCTION

Since combustion instability in solid-propellant rocket motors is such a complex phenomenon, it is desirable to obtain as complete a description of the pressure-time history of an unstable-motor firing as possible: this would be a pressure-time record at every point in the motor cavity, in the nozzle cavity, and at the burning surface of the propellant. The pressure-measuring system should be very accurate, and should be capable of following the most rapid pressure fluctuations very closely. In practice, however, it is not yet possible even to approach this ideal with present instrumentation techniques. As in many experimental investigations, measurements must be made at a few locations within the system, and the structure of the system must be inferred from these.

It is desirable to measure the mean pressure of an unstable firing quite accurately because a pressure-time curve can be used to determine the propellant mass flow, which in turn can be used to determine burning rates and changes in grain geometry. Determination of the burning rate at any time during the motor firing is important because burning-rate changes are often observed during periods of instability. Knowledge of the internal dimensions of the propellant grain is important because it is necessary for the calculation of natural frequencies of the system from acoustic theory (Ref. 1). It is also desirable to obtain good frequency and amplitude data at high frequencies, plus comparative phase and amplitude data at different positions in the motor. When taken from a tubular-motor firing whose frequencies correspond to tangential modes in the port, the high-frequency phase and amplitude data from different positions on the motor are particularly valuable because they can be used to infer the position of the nodal plane.

No pressure-measuring system is now available which combines a high degree of precision with good frequency response; consequently, good instrumentation must be composed of both high- and low-frequency components.

Accuracy of mean-pressure measurements and in determining amplitude, frequency, and phase relationships in a high-frequency system is dependent upon the recording system as well as upon the transducers, and a single recorder usually will not suffice. Considering just the many makes of recording devices and pressure transducers which are commercially available, it is obvious that many different instrumentation systems could be devised for use in studying combustion instability. This paper describes and evaluates the system which has been developed for use at the Jet Propulsion Laboratory.

II. LOW-FREQUENCY PRESSURE-MEASURING SYSTEM

The purpose of the low-frequency system is to obtain an accurate record of the mean pressure. This system utilizes strain-gauge transducers, whose outputs are recorded by galvanometer oscillographs.

A. Transducers

Because during periods of unstable combustion some motors exhibit pressure peaks which are several times as large as the stable mean pressure and because superimposed upon these peaks are high-frequency oscillations of several hundred psi, the transducer is required to be much more rugged than it would need to be for use on a stable firing. Taber Type 176 pressure transducers[4] were used

[4]Taber Instrument Corp., North Tonawanda, N. Y.

on most of the firings made for this study of combustion instability. Pressure in a fluid reservoir in the Taber gauge is used to deform a ring to which strain gauges are bonded. Figure 1 shows the usual location of the Taber gauges on the motor, one at the nozzle end and one at the head end.

The reason for using two gauges is partially to prevent loss of data, commonly c sed by plugging of the gauge lines. The severe pressure oscillations in some of the unstable motor firings often cause partial breakup of the propellant grain, and bits of this propellant sometimes lodge in the pressure taps.

During violently unstable runs, rather large differences have often been noted between the pressure-time curves obtained from the head-end and those from the nozzle-end Taber gauges. It seems plausible that during a part of the run when the mean pressure is changing very rapidly with time there could be a sizable difference between the pressures at points at opposite ends of a motor, particularly one with a large length-to-diameter ratio. On some of the traces where these differences are quite evident, it appears that one of the gauges was partially plugged at some time during the run and later became unplugged and returned to zero at the end. The gauges were not exposed to particularly high temperatures, but they were severely vibrated during unstable runs, and their accuracy in such an environment is not well known. However, during runs which were severely unstable but gave no evidence of grain breakup, the characteristic velocity c^* of the propellant agreed quite well with that obtained from stable motor firings. On the other hand, runs which exhibited evidences of grain breakup also exhibited somewhat larger differences between the head- and nozzle-end pressure traces, and the c^* obtained from these traces was almost always significantly lower than that which was obtained from stable motor firings. Occasionally, higher than normal c^* values were obtained from pressure-time curves of unstable motor firings, but these were usually associated with evidence of gauge plugging.

B. Recording Apparatus

A block diagram of the instrumentation system used is shown in Fig. 2. The signal from a low-frequency Taber gauge is amplified by a Miller Type C-3 carrier amplifier,[5] and the demodulated output of this amplifier is fed to a 460-cps galvanometer in a Miller Model H galvanometer oscillograph,[5] which usually records at 24 in./sec, with a deflection of 250 psi/in. for a 1000-psi maximum deflection. The galvanometer was electrically damped to be down 3 db at 90 cps. Damping was needed to eliminate a beat frequency which was a combination of the carrier frequency and the frequency of pressure oscillations in an unstable motor and to reduce galvanometer oscillations following ignition. Figure 3 shows a pressure trace obtained with an undamped galvanometer from a motor during a period of moderate instability. The amplitude of the beat frequency here is large enough to make the determination of the mean pressure inaccurate. During motor firings exhibiting more severe instability, this effect was large enough to make the mean-pressure data worthless. The damping is merely an averaging process, and does not appear to cause loss of data.

Also included on the Miller record were an ignition signal, a 100-cps timing signal, detector traces (to be explained later), and reference lines spaced at 10-millisec intervals, as shown in Fig. 4.

[5]Consolidated Electrodynamics Corp., Pasadena, Calif.

The output of the Miller carrier amplifier which was connected to the head-end Taber gauge was fed to a Sanborn Model 127T recorder.[6] Records from this recorder were used for qualitative comparison of motor firings.

III. HIGH-FREQUENCY PRESSURE-MEASURING SYSTEM

The purpose of this system is to measure accurately the amplitude and frequency of the oscillating component of pressure, over as wide a frequency range as necessary. The response of this system is good from a few hundred cycles per second to 15 kc; the present investigation has so far indicated no need for a system with wider frequency range.

In addition, relative phase measurements should be provided by the high-frequency system.

A. Transducers

A high-frequency pressure transducer which is to be used on an unstable rocket motor must be rugged enough to withstand ordinary handling shocks as well as the high accelerations which are imposed upon it by the unstable motor. It must also have a provision for adequate cooling, or be able to operate at relatively high temperatures without cooling. An examination of Table 1 shows that, of the high-frequency gauges which were tested, the Photocon,[7] a variable-capacitance transducer, is markedly less sensitive to acceleration than any of the others.

[6] Sanborn Co., Waltham, Mass.

[7] Photocon Research Products, Pasadena, Calif.

Some of the data for this Table were obtained by applying a pressure step to each gauge by means of a shock tube. Each gauge would overshoot and momentarily oscillate at its natural frequency. The frequency response obtainable from the Photocon gauge is actually the frequency response of the Photocon and Dyna-Gage[7] system. The relative response of the Dyna-Gage drops off very sharply beyond 15 kc. It can be seen from Table 1 that the natural frequencies of the Photocon gauges occur where the relative response of the Dyna-Gage unit is rather low, causing the measured overshoot to be correspondingly low.

1. Effects of position. The position at which the Photocon transducers were attached to the motors is shown in Fig. 1. A disadvantage resulting from the position of the Photocons on this particular headplate design is that the faces of the Photocons are recessed slightly from the end of the grain. The Photocons mounted in the position shown are well located for measuring amplitudes of longitudinal modes, but they are in a less advantageous position for measuring tangential modes, since the face width of the gauge is a significant fraction of the port diameter. At any instant during instability, a pressure gradient very likely would exist across the face of the gauge. However, the error introduced by this was estimated to be small.

On all of the firings of motors with initial port diameters of less than 4 in., the faces of the Photocons not located on the longitudinal axis were entirely or partially covered by the 1/4-in.-thick restrictor plug, which caused an unknown, but presumably small, error.

2. Effect of temperature. The Photocon transducers used in the unstable rocket motor firings were apparently adequately cooled. Zero shifts in Dyna-Gage

output voltages were observed occasionally after highly unstable runs. These were felt to be the result of increased heat transfer rates which impaired the accuracy of the mean pressure records but which seemed to leave the a.c. component relatively undisturbed and did not appear to be accompanied by gauge damage.

When these transducers were installed in motors which had been conditioned to subfreezing temperatures, care was taken to dry their internal cooling passages with a blast of air before attaching them to the motor. This was done to prevent plugging of the coolant passages with ice, which would result in a burned-out diaphragm. A thin coating of zinc chromate putty was applied to the face of each Photocon to further reduce the danger of overheating by reducing the heat transfer rate through the diaphragm.

3. Effect of variation in installation torque. The manufacturer recommends that the Photocon transducers be installed with 300 lb-in. of torque. A 1000-lb and a 2000-lb Type 355 Photocon gauges were calibrated at several values of installation torque, from 30 to 400 lb-in. A maximum deviation from the 300 lb-in. calibration of 3.7% was observed at an installation torque of 30 lb-in.

4. Acceleration effects. The measurement of amplitudes of relatively low-level oscillations, from 2 to 50 psi, was not particularly difficult because the transducers were subjected to low acceleration levels. When the peak-to-peak amplitude of the high-frequency component of the pressure approached the magnitude of the mean pressure, the acceleration levels on the headplate of the motor became very high, and large errors were introduced. Figure 5 shows a motor secured on the test stand prior to firing. The motor rests on V-blocks, and the headplate rests against two vertical blocks which are welded to the stand, and

whose faces are covered with approximately 1/8 in. of lead. Three heavy chains were drawn across the motor case and screw-tightened. Accelerometers were placed at various positions on motors which became unstable during firing.

The results of the first unstable-motor tests which employed accelerometers mounted on motor cases indicated exceedingly large accelerations which were well beyond the range of the accelerometers. Further tests were made in which accelerometers with the highest ranges available were mounted near points on the motor case (usually on the outer edge of the headplate) which were assumed to be near nodal points. Amplitudes of acceleration from the most violently unstable motor firings reached 10,000 to 20,000 g's. That the acceleration levels which were measured were extremely high--of the order of several thousand g--was well established, but their magnitudes were uncertain for two reasons. First, sine-wave calibrations of the accelerometers at these high levels was impossible when the tests were conducted. Second, the wave shape obtained from these high-range accelerometers indicated that they had often been overranged.

In order to overcome the effect of acceleration on the Photocon transducers, a new steel headplate (Fig. 6) was designed and fabricated. This new headplate was 4 in. thick at the point where the gauges were mounted. It was bolted near the outer edge to a heavy steel plate (Fig. 7) which was in turn bolted to the test stand. The value of this method of eliminating the error caused by acceleration was checked in two ways. First, this headplate had been designed with four positions to mount Photocons. One of these holes was blind and was located slightly farther from the axis of the axis of the motor than were the other. Motor firings were made with gauges in all four positions, and the blind gauges always showed very low-amplitude outputs. An adapter was used to install a blind gauge in a normally pressure-sensing position on the headplate, and additional firings were made in this manner (Ref. 2). A typical record from a firing of this type is given in Fig. 8. All of the records obtained from firings using blind gauges on this massive headplate bolted to the test stand indicated that the acceleration error using this system was extremely small. Additional tests were made using blind and pressure-sensing gauges on the standard headplates. The large acceleration outputs obtained during periods of severe pressure oscillations can be seen in Fig. 9. Use of the massive headplate bolted to the test stand proved to be inconvenient, and caused a delay in firing which was particularly undesirable for firing temperature-conditioned motors.

Calculations were made in an attempt to estimate the acceleration amplitudes to be expected if the headplates alone were vibrating. These calculations predicted much lower over-all acceleration levels than those which were measured, and they did not predict significant differences in acceleration levels between the standard and heavy headplate designs. These results suggested that the acceleration effects were accelerations of the motor as a whole and not primarily diaphragm vibrations of the headplate. However, further tests will be conducted using blind and pressure-sensing Photocon gauges on strongly unstable motors with the massive headplate not bolted to the test stand.

Another unusual hazard to which both sets of pressure transducers were subjected was the tendency of the motor to twist about its longitudinal axis during an unstable run. This rotation was often enough to press one of the Photocons against one of the thrust blocks and to cause the nozzle-end Taber gauge to strike the test stand.

B. Recording Apparatus

Two 2000-lb transducers were commonly used to record the high-amplitude pressure oscillations and were calibrated to give full-scale deflections of 1000 psi on the recording devices. A third gauge was used primarily to record low-amplitude pressure oscillations. The Dyna-Gage unit used with this gauge was adjusted so that its output voltage would be zero when the gauge was sensing the approximate mean pressure at which the onset of instability was expected, and it was calibrated to give a full-scale peak-to-peak deflection of 200 psi. A 500- or 1000-lb Photocon was usually used in this manner, depending upon the anticipated pressure levels.

The outputs of the Photocon Dyna-Gage system were recorded in three different ways. They were a.c.- or d.c.-coupled to a Hathaway Instruments Type SC16-A high-speed cathode-ray-tube oscillograph.[8] The a.c. trace was high-pass filtered to be down 3 db at 55 cps. This instrument would record at 200 in./sec with a maximum deflection of 1 in. The Hathaway record also included references lines with a 1.0-millisec spacing, a 100-cps timing signal, and an ignition signal. Examples of this record may be seen in Fig. 8 and 9.

After an unstable motor firing, the Photocon gauges would often show an appreciable zero shift. Because of this, the mean-pressure data from the Photocon gauges were not reliable, but the d.c. output from one of them was usually recorded by the Hathaway to indicate sudden changes in mean pressure.

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[8]Hathaway Instrument Div., Hamilton Watch Co., Denver, Colo.

The a.c. outputs of the Photocon system were recorded at 60 in./sec on AM channels of a modified Ampex Model 306-7 7-channel tape recorder,[9] along with the ignition and timing signals.

For the third record of the Photocon system, called the detector, the Dyna-Gage outputs were high-pass filtered, usually at 2400 cps, full-wave rectified, and the resulting signal fed to undamped, 100-cps galvanometers in the Miller recorder. The 2400-cps cutoff was chosen because the lowest frequency of interest in this study was found to be approximately 3 kc. These signals were usually amplified to give a deflection of 30 psi/in. but this was increased to 5 psi/in. on one channel for each run, so that relatively low-level instability could be detected. The purpose of this system was to detect the onset of instability at the earliest possible time during the run, and to provide an easy method of correlating pressure oscillations with changes in mean pressure.

C. Evaluation of System

A series of tests was conducted on the high-frequency instrumentation system to determine the phase shift between channels and the waveform distortion caused by relative phase shifts between components of different frequencies.[10] In each case the high-frequency system was set up as it would have been for a motor firing, except that the mean pressure level was simulated by loading a Photocon in a dead-weight tester, and the pressure oscillations were simulated

[9] Ampex Corp., Redwood City, Calif.

[10] Personal communication from G.A. Wiker, Instrumentation Section, JPL.

by a reactance modulator connected between the Photocon and the Dyna-Gage. The reactance modulator was connected to an audio oscillator.

1. Absolute phase shift. For the determination of absolute phase shift, the output of the audio oscillator was sent through a low-impedance line to one set of plates of an oscilloscope, and the other set of plates was connected to the previously described channel at the Hathaway input, which, electrically, was the same point as the input to the Ampex direct-recording amplifier. The balance of the oscilloscope amplifiers had been checked previously. The resulting Lissajous figure showed the phase shift of the system except for that introduced by the recording devices. The measured phase shift was less than 1 deg for frequencies up to 1 kc. It increased nearly linearly to 11.5 deg at 5 kc, and then increased much more rapidly to 90 deg at 20 kc. These data indicated that a complex waveform with components much over 8 kc would probably be considerably distorted, and that an accurate determination of the shape of a nonsinusoidal wave with a fundamental frequency from 3 to 7 kc, similar to those which have been observed in this study of combustion instability, would be quite difficult.

2. Relative phase shift. The relative phase shift between two channels was measured in a similar manner, except that the same oscillator signal was sent to two channels and the output signals were used to make a Lissajous figure. This phase shift was nearly linear up to 5 kc, increasing from 6 deg at 1 kc to 19.8 deg at 5 kc and to 43.3 deg at 17 kc. These results indicate that in order to measure a phase difference between pressure signals from gauges at different locations on a rocket motor a determination of the relative phase characteristics of the system would have to be made prior to the motor firing using exactly the

same components which would be used on the motor firing. In addition, experience indicates that high-speed photography would be required to obtain a measurable record of the rapidly changing Lissajous figure.

3. Switching response and Hathaway trace alignment. An additional test was made in which Hathaway records were obtained both by switching two channels on simultaneously at the Dyna-Gage input and be switching them on at the Hathaway input. The relative shift between the two channels was too small to be measured accurately, but was determined to be less than 25 μsec, which would cause a shift of 2.5 % at 10 kc. In order to obtain this precision, it would be necessary to determine the error in alignment of the Hathaway traces, which is of the order of 0.01 in., or 50 μsec at 200 in./sec. Direct measurement of phase shifts from the Hathaway record of signals with frequencies over 1000 cps does not appear to be practicable.

4. Over-all frequency response. The over-all frequency response of the Photocon, Dyna-Gage, and tape system, excluding the mechanical response of the gauge, was determined by recording an oscillator-generated signal on the tape. The same test setup was used for the relative-phase-shift test. The voltage amplitude at the tape input at 1000 cps was used as a standard and was compared to the tape output voltage amplitude during playback. The response curves thus obtained varied somewhat between channels but were, at worst, 100 ±7% from 500 cps to 15 kc. This tape was recorded by the Hathaway recorder, and the resulting frequency response (again in the worst case) varied from 80 to 100% of the 1000-cps reference from 500 cps to 15 kc with a sharp cutoff at 15 kc which was not observed in the case of the tape. The response of the system within this

frequency range appears to be reasonably good, although improvement might be hoped for. Amplitude corrections could be applied to improve accuracy.

5. Overload of tape system. In the study of combustion instability, it is often not possible to obtain a good estimate of the amplitudes of pressure oscillations which will be obtained from a proposed motor firing. Oscillations which greatly exceed expected values and therefore exceed full-scale calibrations are frequently encountered. On the Hathaway record, the deflection of the trace is space-limited, and in the case of the detectors, the trace goes off the paper; in either case, the actual amplitudes cannot be determined. Therefore, it was desired to determine the characteristics of the tape record under overload conditions.

A test was conducted to determine the overload characteristics of the d.c. amplifier and Ampex tape recorder system. The recording system was set up at a calibration level of 0.943 v rms at 1000 cps at the Ampex input. The test results indicated that the amplifier was linear within 3% from the initial calibration level to a five-fold overload. The amplifier and tape system showed only a 9% attenuation at a five-fold overload, beyond which the relative response dropped off quite rapidly. The predominant distortion which was observed was the third harmonic. This increased linearly from zero at the calibration level to 12% at the five-fold overload point. The second and fourth harmonics were also present, but their combined distortion effect was small, being less than 2% at the same point. The test indicates that tape data taken at a level considerably beyond the full-scale calibration are not greatly in error, and the amount of the error can be estimated for a reasonable amount of overload.

D. Frequency Analyzer

The taped record of the Dyna-Gage outputs was analyzed by a ten-band frequency spectrum analyzer developed at JPL primarily for use with this research project. The first band of the analyzer record is the taped record which has been filtered by a 1500-cps low-pass filter. The remaining nine channels are 1500 cps in width, but the recorded signal in each channel is the difference between the input signal and an oscillator-generated signal which is the band center frequency. An example of this record is given in Fig. 10. For bandwidths of 1500 cps, this recorded signal is always less than 750 cps and can be satisfactorily recorded by low-frequency oscillograph galvanometers. Oscillators and filters can be readily changed so that different bandwidths can be constructed. The system was also used extensively for analysis of low frequencies by changing the bandwidth to 300 cps (Ref. 3).

Using a bandwidth of 1500 cps, frequencies could be read out to the nearest 15 cps by counting cycles for 0.03 sec. Most frequencies measured during this study of combustion instability decreased linearly with time. The decrease in frequency for a typical unstable motor firing during a period of 0.03 sec is approximately 30 to 45 cps, or between 0.5 and 1.0% of the measured frequency. The system's transient response to a suddenly applied sinewave was checked, and a time of 2.5 millisec for 90% response was obtained. Frequency-time plots obtained from two Photocons on the same motor usually agreed at any time during the period of instability to within 1%.

E. Relative Amplitude Measurements

A comparison was made of high-frequency pressure-amplitude data recorded by the Hathaway recorder, the detectors, and the frequency analyzer. These records were read at 0.01-sec intervals for several runs which exhibited moderately high pressure amplitudes. A plot of pressure amplitude vs time from ignition which contains data from these sources is presented in Fig. 11. Since the Hathaway record is the most direct record available and has the best frequency-response characteristics, it was considered to be the most accurate of the three. If the Hathaway record is taken as the standard, it can be seen that the averaging characteristics and poorer frequency response of the detector and frequency-analyzer record introduce considerable error into the amplitude measurements.

IV. FUTURE REQUIREMENTS

Of all the aspects of high-frequency system performance, the area in which the present system is the weakest is in relative phase measurements. It is doubtful that this problem has been considered nearly as much as have the problems of vibrational and high-heat-transfer environments and frequency response. It seems likely, however, that phase measurements from high-frequency systems would be useful in instrumentation applications other than those used in the study of solid-propellant combustion instability, Attempts to improve this aspect of performance might be worthwhile.

The instrumentation system which is now in use for this study of combustion instability is believed to be the best that is currently available. Certain improvements in the system, particularly in the transducers, would greatly increase the amount of useful data obtained from each motor firing. High-frequency transducers are needed which are smaller, more rugged and reliable, and less sensitive to acceleration. Improved ability to measure very-low-amplitude fluctuations superimposed upon a large mean pressure would be very desirable. As for the low-frequency transducers, some means of increasing reliability by preventing plugging without sacrificing accuracy is also needed.

V. SUMMARY

A description and evaluation of the instrumentation used in solid-propellant rocket motor combustion instability research at the Jet Propulsion Laboratory has been given. The major area of concern has been the determination of the frequency, amplitude, and mean values of the pressure oscillations within the rocket motor. Phase shifts within the system have also been studied. The methods used to evaluate the performance of the instrumentation have been presented. It should be noted that the effect of the gauge was not actually considered in most of the evaluation tests conducted. An exact reconstruction of the chamber phenomena from the recorded data is, therefore, impossible. To do this, the system must be evaluated by applying to the gauge pressure oscillations at the frequencies and amplitudes of interest. It does not appear that this will be possible in the near future. Fortunately, it appears that the research scientist is presently able to obtain much useful information from the present instrumentation system.

Table 1. Evaluation of high-frequency pressure transducers.

Transducer	Rated pressure, psi	Rated linearity, %	Pressure step applied, % of full scale	Overshoot, % of step	Ringing frequencies, kc	Acceleration sensitivity, psi/g	
						With H_2O	No H_2O
Dynisco PT-49[a]	2000	0.5	4.7	70	30	0.05	0.03
Photocon[b]							
307	1000	2.0	13	15	35	--	--
345	2000	2.0	7.5	10	35	0.0048	0.0036
355	2000	2.0	--	--	--	0.0032	0.0032
Elastronics[c]							
6008	70	0.1	38	10	45	0.06	0.05
6009	2000	0.1	7.5	20	55	0.02	0.02
Kistler (SLM) PZ-14[d]							
Serial 1233	3000	1.0	4.2	30	47	--	0.04
Serial 1237	3000	1.0	3.0	30	47	--	0.04

[a]Dynamic Instrument Co., Cambridge, Mass.

[b]Photocon Research Products, Pasadena, Calif.

[c]Elastronics, Inc., Reseda, Calif.

[d]Kistler Instrument Co., Inc., Tonawanda, N.Y.

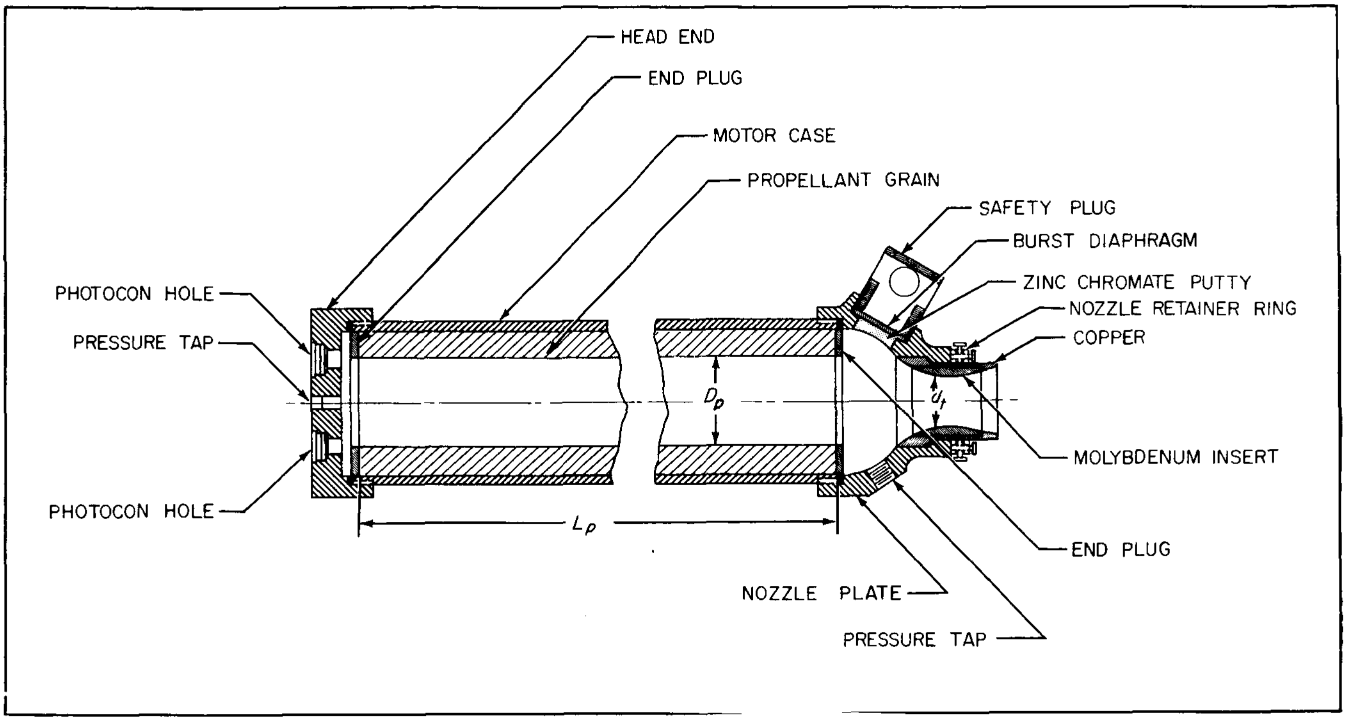

Fig. 1. Sectioned view of tubular motor.

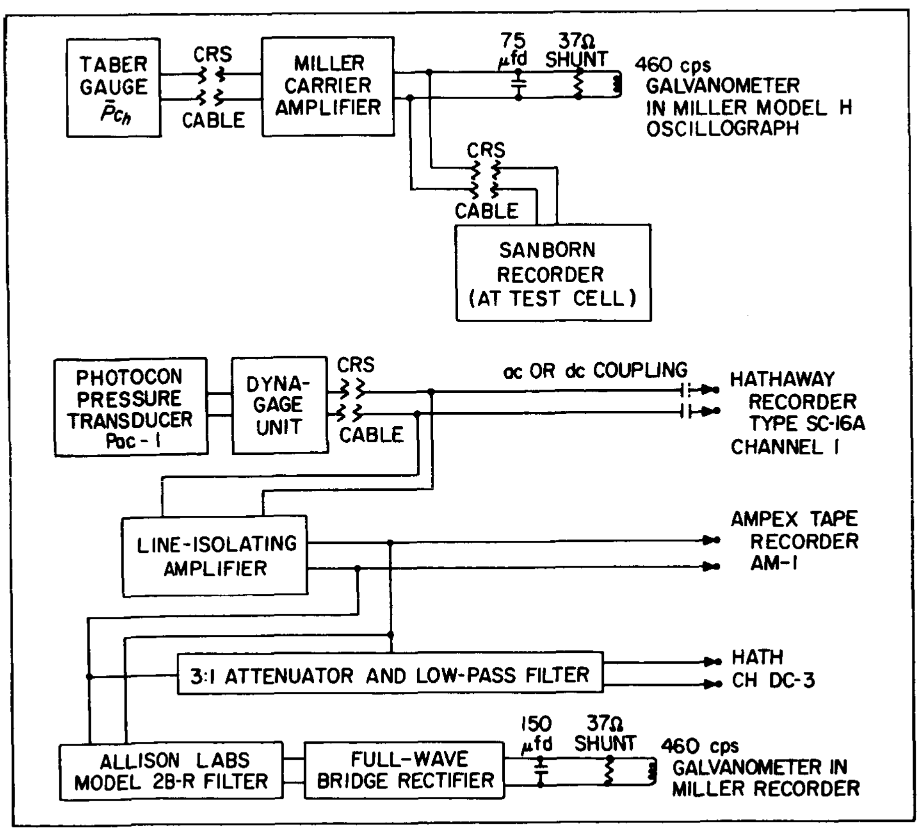

Fig. 2. Instrumentation block diagram.

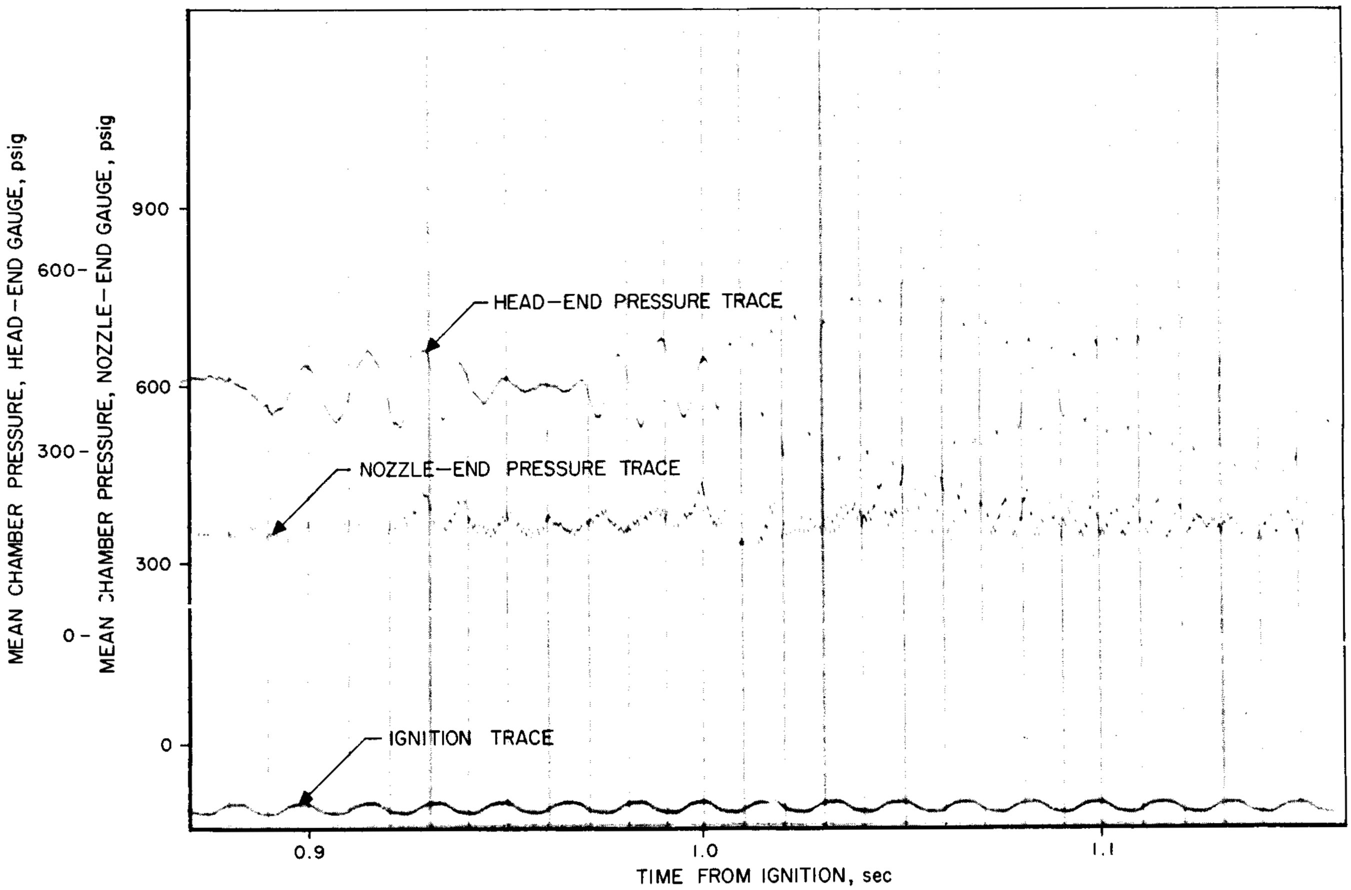

Fig. 3. Undamped Miller record.

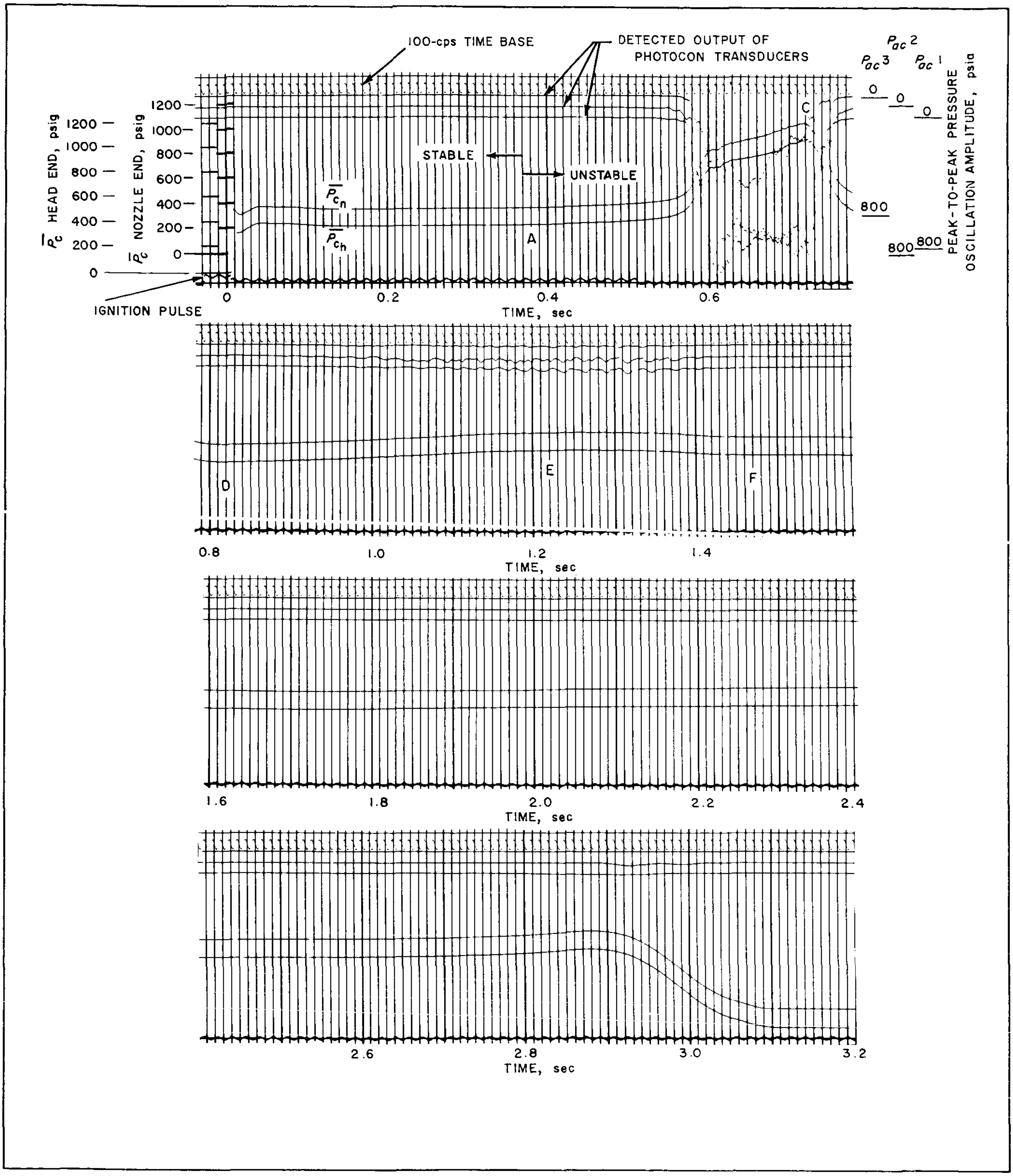

Fig. 4. Miller record, typical unstable firing.

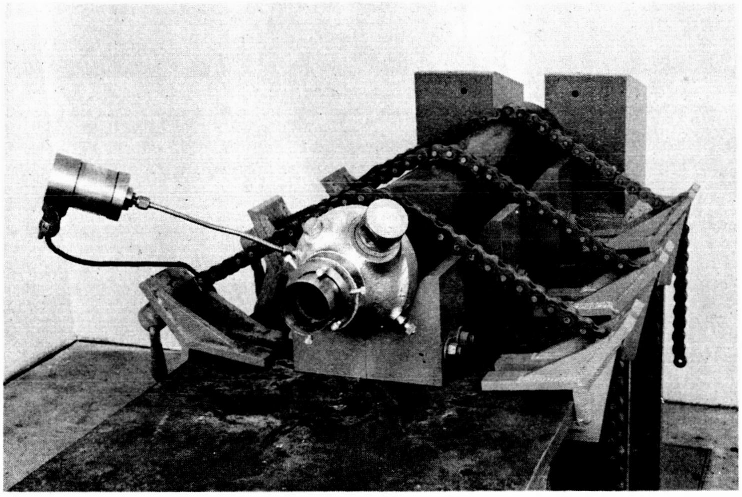

Fig. 5. Instrumented motor in test stand.

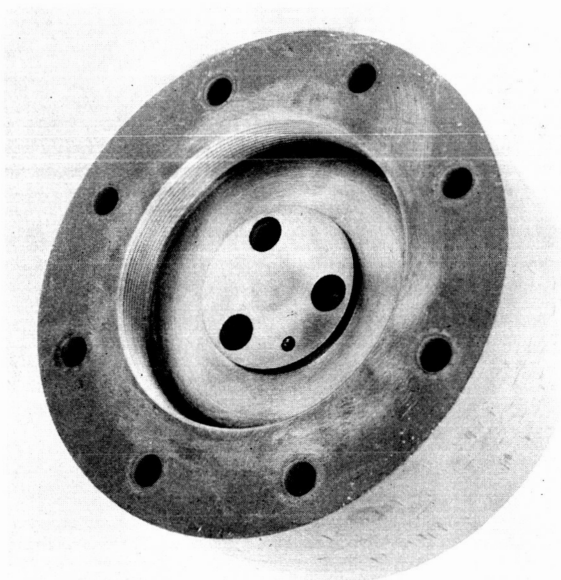

Fig. 6. Massive headplate.

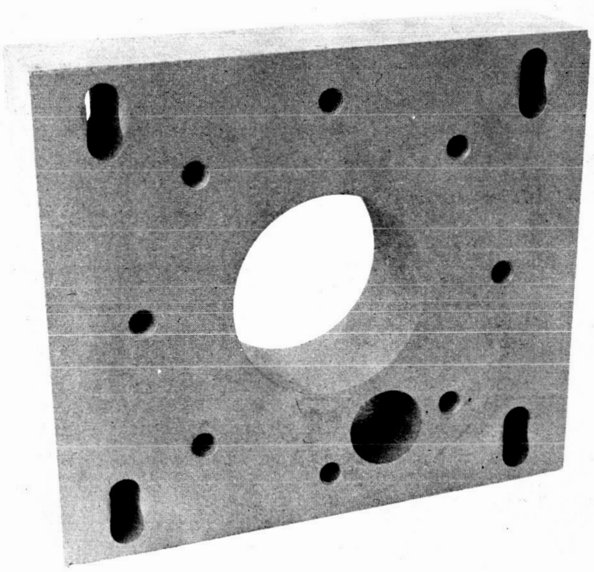

Fig. 7. Thrust block.

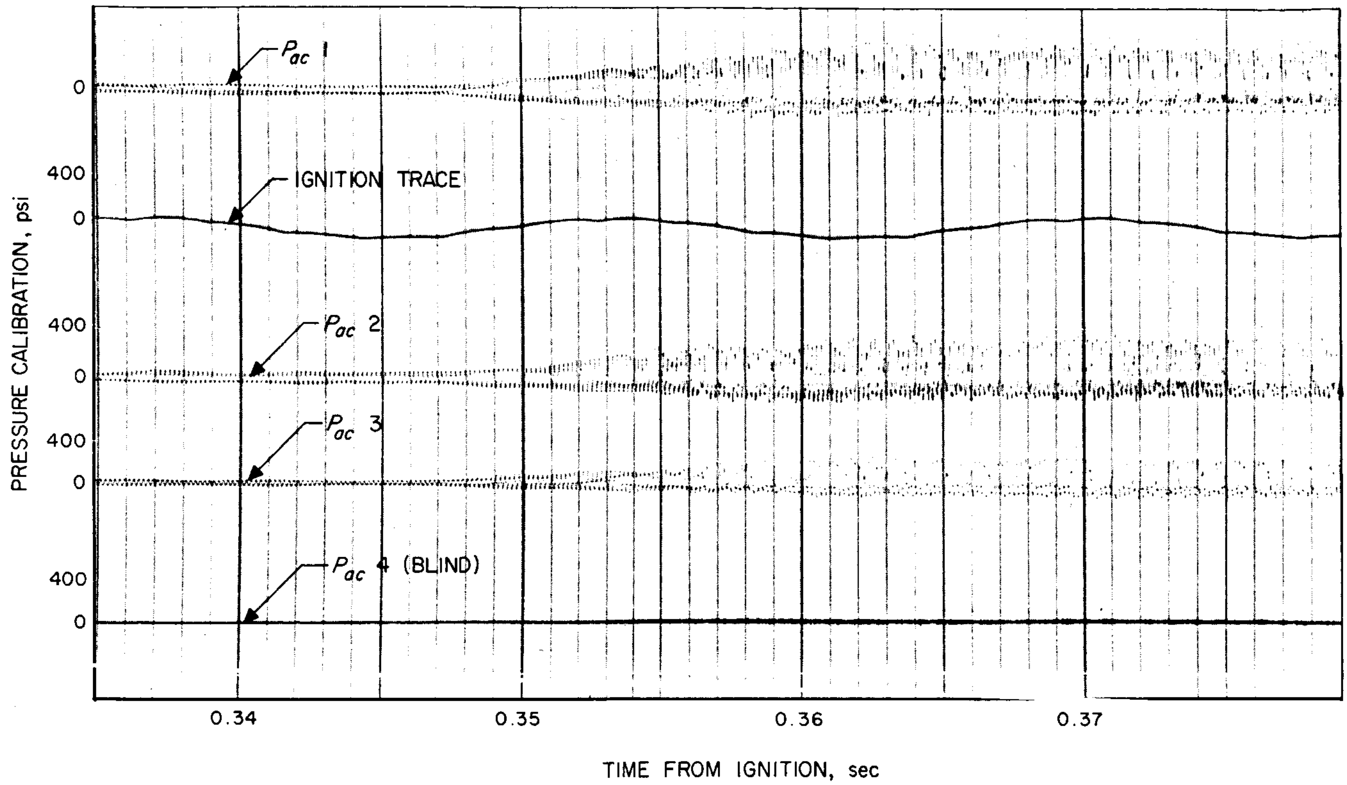

Fig. 8. Hathaway record, massive headplate.

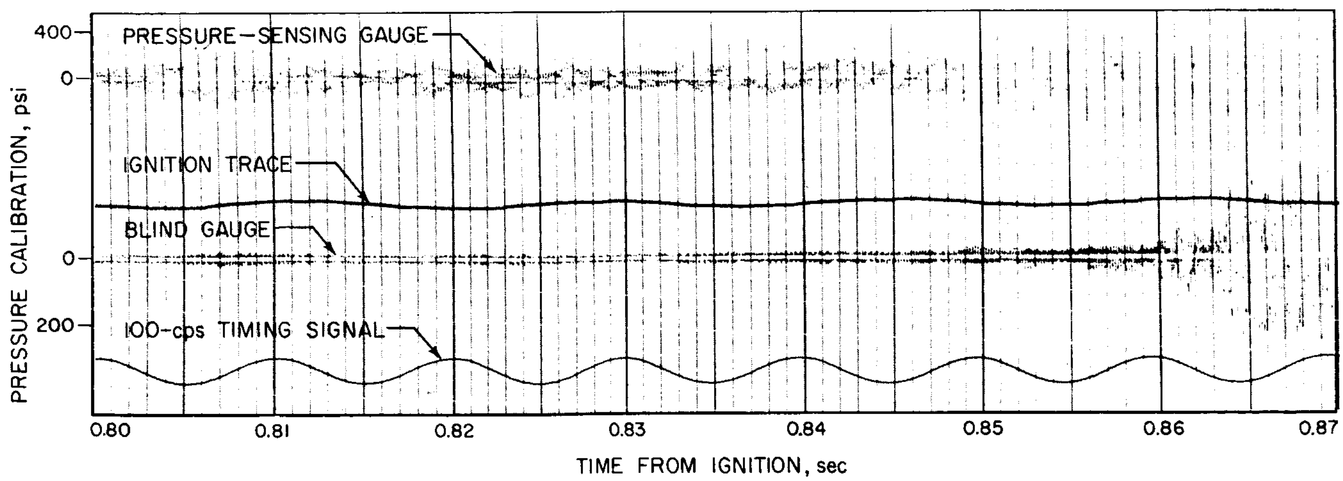

Fig. 9. Hathaway record, standard headplate.

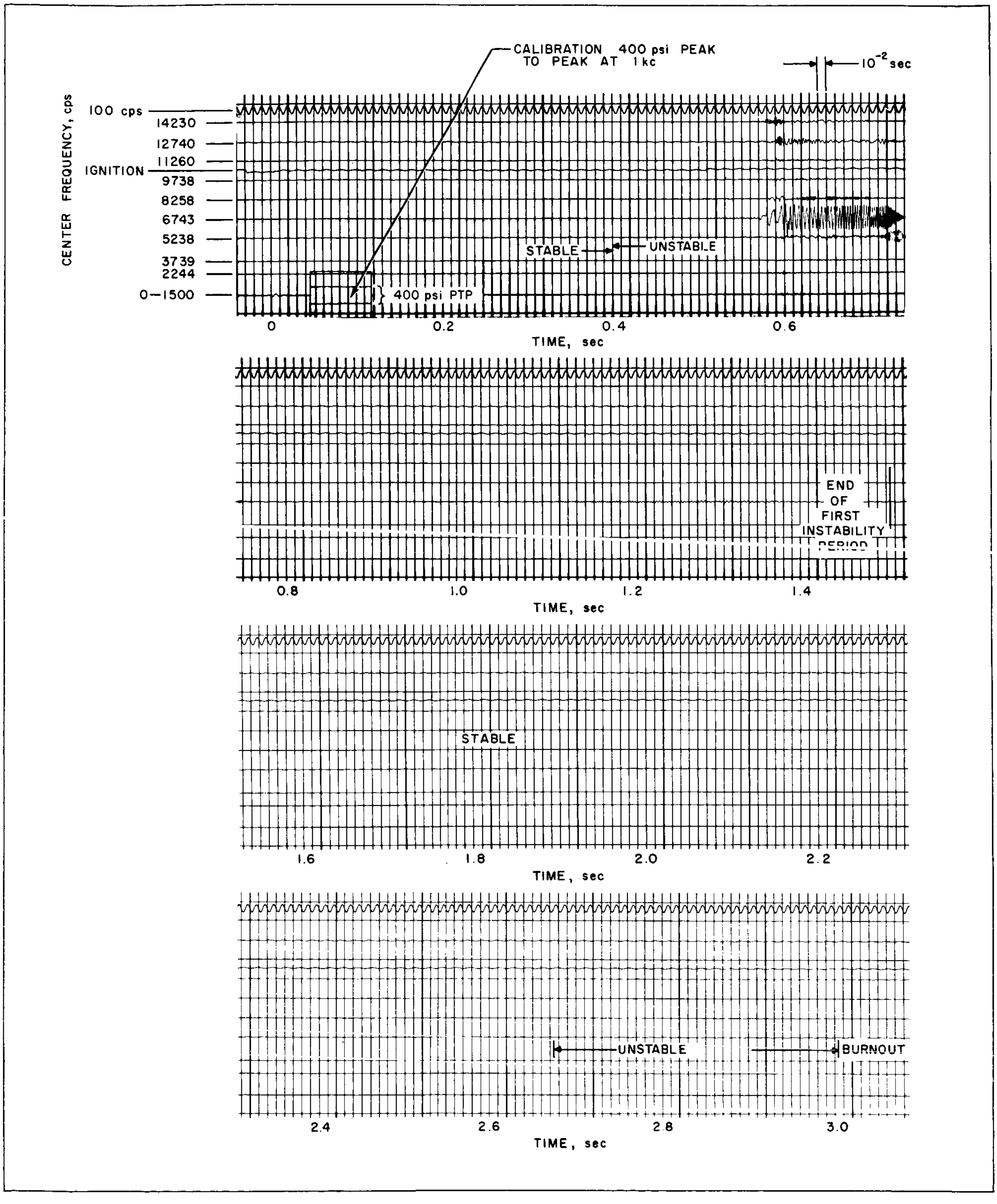

Fig. 10. High-frequency-analyzer record, typical unstable firing.

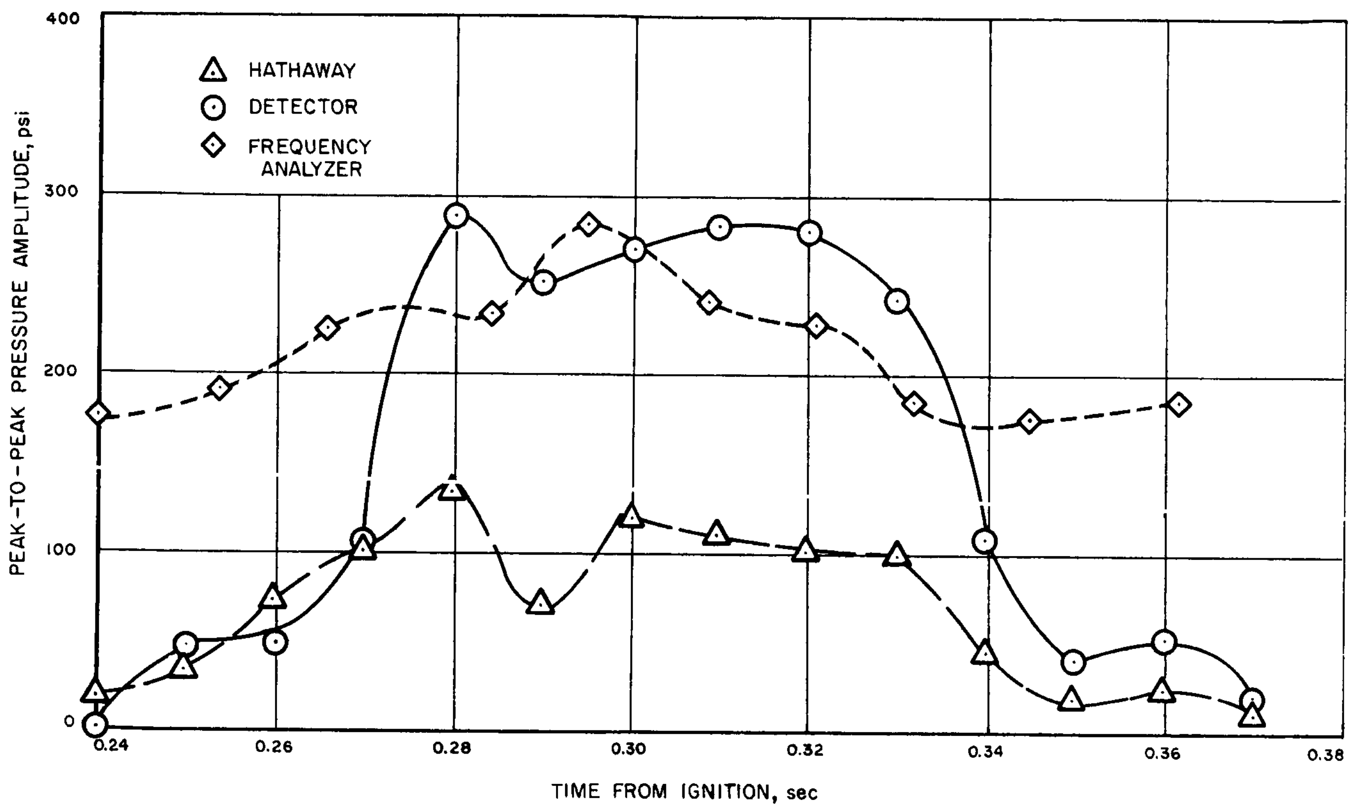

Fig. 11. Pressure oscillation amplitude measurements obtained from Hathaway record, detectors, and frequency-analyzer record.

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